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Prototyping to Leverage Learning in Product Manufacturing Environments

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Abstract

Rooted in the automotive industry, this article discusses the topic of leveraging tacit knowledge through prototyping. After first providing an overview on learning and knowledge, the Socialization, Externalization, Combination and Internalization (SECI) model is discussed in detail, with a clear distinction between tacit and explicit knowledge. Based on this model, we propose a framework for using said reflective and affirmative prototyping in an external vs. internal learning/knowledge capturing and transfer setting. Contextual examples from select automotive manufacturing R&D projects are given to demonstrate the importance and potential in applying more effective strategies for knowledge transformation in engineering design.

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Keywords: knowledge transfer; internal reflective prototyping; prototyping; tacit knowledge; integration events; product development

1. Introduction and Background

In this article, we argue for the use of explorative and analytical approaches in product development processes by discussing tacit knowledge accumulation and transfer through prototypes. With this intention, we attempt to make several contributions to current literature.

Firstly, we present a mapping of relevant literature on the topic of knowledge, especially related to product development. In this section, we are exploring organizational and individual knowledge, the differentiation of tacit and explicit knowledge, in addition to some current practices on the transfer of (tacit) knowledge.

The second contribution is to present a model of prototyping categories, with special emphasis on the differentiation between learning and verification as the main intent for prototyping activities. A model of four prototyping categories is proposed, and discussed in relation to dealing with known and unknown problems concerning tacit knowledge in product development.

The article closes by exemplifying the previous two sections by providing insights from two industry cases. The use of analytical and explorative approaches to prototyping are discussed, and several possible research opportunities are presented.

The automotive industry—an industry with steadily increasing demand for faster development cycles and higher quality products—is subject to increasing competitive pressure. Making mistakes is costly in an industry where product life cycles are in the order of five to ten years, and late-stage design changes have major implications for manufacturing planning and processes. In addition, automakers need to rely on previous experience, and cannot start from scratch in each development project. The use of process and part standardization within the product technology platforms is a well-established practice to reduce the burden on the development teams. Hence, much research is currently targeting knowledge and learning mechanisms in new product development. Examples include knowledge-based development (1)—a method for extracting basic principles of Toyota's product development processes (2).

In this paper, we focus on analytical and explorative approaches, and their relation to both creation and transfer of tacit knowledge in product development.

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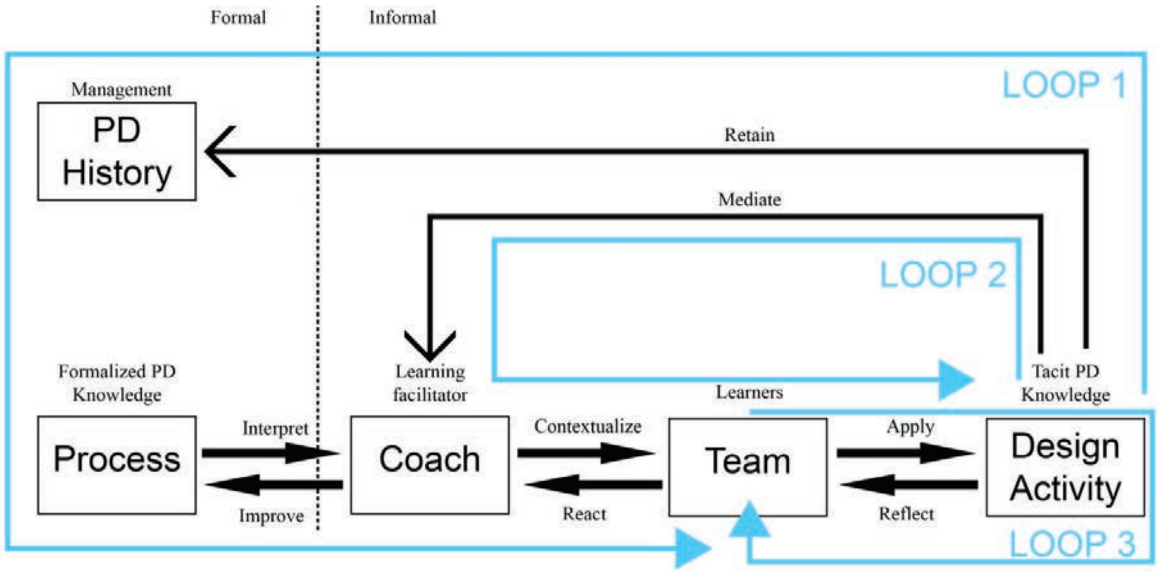

Figure 1 - Learning mechanisms in product development, adopted from (9) and (10).

2. Theory: Knowledge in Product Development

In (3), Ulonska presents numerous definitions of knowledge found in product development. Rowley differentiates knowledge and wisdom (4) by defining knowledge as application of data and information ("know-how"), whereas wisdom is defined as elevated understanding ("know-why"). Additionally, it can be argued that knowledge can be further divided into individual and organizational knowledge (5). The sum of what is learned, experienced, discovered or perceived (by individuals) during a project (in the organization) defines organizational learning. The interactions of individuals are the main ingredients of organizational knowledge, and the knowledge of these individuals is called individual knowledge. This is categorized in three categories; experience-based, information-based and personal knowledge (6). Nonaka and Takeuchi argue that the organizational knowledge exists between (and not within) individuals (7).

2.1. Defining Integration Events and Knowledge Owners

Most product development organizations use stage-gates for decision making. The stage-gate model is a financially-based governance method, which leverages the importance of financial decisions during development. However, this type of process governance often makes event-based technological decisions harder. Hence, there is a call for a more event-based governance model in product development (8). An example on such events can be the emerging trend of hosting 'integration-events'. These events are so-called learning cycle gates, and aim at ensuring better insights and information while preserving previous project know-how and learnings. This way, large product development organizations aim at transferring project (individual) knowledge into organizational learning. Here, informal knowledge is formalized (made explicit), and formal knowledge is interpreted (by the individuals). The key to successful organizational learning is a mutual exchange of these two kinds of knowledge.

Some companies employ key experts or learning facilitators as catalysts for the exchange of knowledge within their organization. These so-called knowledge owners are usually technical or functional managers, who help preserve and facilitate the learnings and insights. Examples of key experts are Toyota's functional managers who owns the technology. The functional managers employ existing knowledge within projects, while so-called chief engineers challenge the existing standard by being the customer representative. By spending time with and on the development team, these key experts gain experience and insights, which in turn will contribute to organizational learning inside the company.

By taking a closer look at learning mechanisms in product development in Fig. 1—first introduced by Eris and Leifer (9), and then further iterated by Leifer and Steinert (10)—the distinction between formal and informal knowledge is clarified. Key experts are usually working in the informal area (i.e. learning loops two and three), whereas the organization as a whole operates in the formal area (i.e. learning loop one).

2.2. Tacit and Explicit Knowledge in PD

The terms tacit and explicit knowledge are closely linked to formal and informal knowledge. Explicit knowledge consists of information, facts and numbers that have been formalized (learning loop one from Fig. 1) (11), and they can be summarized into so-called 'knowledge artifacts' (12). Examples on these knowledge artifacts include the widespread use of A3 sheets in the Toyota product development system (2,13), which usually contain condensed explicit information about a project or system. Tacit (or informal) knowledge includes everything non-explicit, hereunder learnings, know-how, craft and skill of the product engineering individuals, accumulated in learning loops two and three (14). We argue that one key dimension of tacit knowledge is the interaction with (and use of) objects and experiences in the product engineering processes, often referred to as prototypes in one form or another.

2.3. The SECI-model and Transfer of Knowledge in PD

First proposed by Nonaka, Toyama and Konno (15) as a prevalent model for enhancement of knowledge creation through conversion of tacit and explicit knowledge, the SECI process (Fig. 2) can be used for describing the different stages of knowledge transfer. The SECI model consists of four stages, including socialization, externalization, combination and internalization, and is used to describe how various knowledge is transferred (in an organization) by spiraling through the four stages. Four knowledge assets are presented as facilitators of knowledge creation, and are categorized as experimental, conceptual, systemic and routine. The latter has gotten increasing support since its first appearance, and a study by Chou and He (16) concludes conceptual knowledge assets (i.e. PD insights) to have the most effect on knowledge creation.

By further studying the model, we can categorize the three stages socialization (tacit-to-tacit), internalization (explicit-to-tacit) and externalization (tacit-to-explicit) as forms of either creation or transfer of tacit knowledge in development teams. The last stage, combination (explicit-to-explicit), can be described as an implemented knowledge repository, where the formalized knowledge within the organization might be distributed to sub-groups that require this knowledge. In the context of transferring tacit knowledge, socialization includes creating a work environment that encourages understanding of expertise and skills through practice and demonstrators. Externalization, or the act of formalizing the tacit knowledge, aims at feeding this into the organization. Similarly, internalization aims at interpretation of formal knowledge, and includes conducting experiments, sharing results, and facilitating prototyping as a means of knowledge acquisition (15). Chou and He (16) also conclude that conceptual knowledge assets—i.e. "knowledge articulated through images, symbols and language" (15)—are the most efficient tool for facilitating externalization and internalization.

2.4. A Proposed Model of Prototyping Categories

In (17), prototypes are defined as "An approximation of the product along one or more dimensions of interest", thus including both physical and non-physical models. Examples include (but are not limited to) sketches, mathematical models, simulations, test components and fully functional pre-production versions of the concept (18).

We argue that prototyping can be divided into four different categories (Fig. 3) (19). The horizontal axis—the intent of the prototype—is split into two sub-categories; "reflective" and "affirmative". The vertical axis, displaying the target audience of the prototype, is spit into "internal" and "external". This two-by-two matrix gives four different prototyping categories which will be briefly explained below.

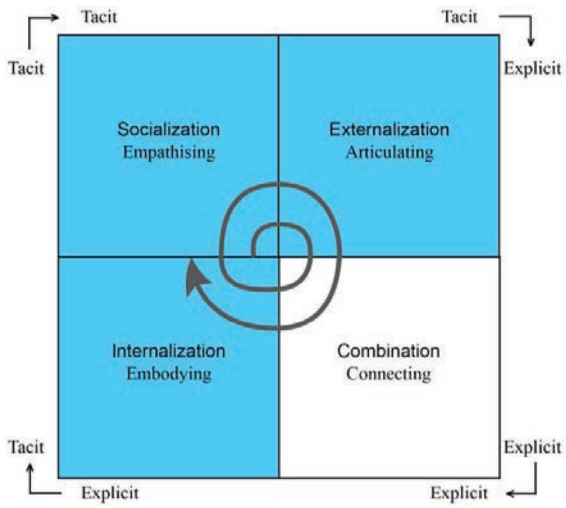

Figure 2 - The SECI-model, with blue areas highlighted as areas of interest, adopted from (15).

2.4.1. External, affirmative prototyping

Typically used for making pre-production models, this kind of prototyping approximate a nearly finished model, and are often termed alpha and/or beta prototypes (20) intended for validation or showcase purposes. These prototypes are high fidelity (i.e. highly detailed) models, used for external validation (e.g. certification test etc.), marketing, or in-depth customer interaction. In an automotive setting, these may be the cars subject to road testing, being pre-production cars tested on closed test circuits by external users.

2.4.2. Internal, affirmative prototyping

Focused in terms of function, this type of prototyping is intended for function, reliability and feasibility testing. Examples include combinations of subsystems, fatigue testing of conceptual prototypes or project milestones to validate team progression. Although high in fidelity (regarding function and complexity), these prototypes are still rarely shown to public audiences. Automotive examples on this kind of prototyping includes running lifecycle testing of components, like shock absorbers, axles and other moving parts.

2.4.3. External, reflective prototyping

Companies often seek feedback from external sources by showing off concepts. User interaction is carefully observed and recorded for further study, and responses and reactions are used for further improving other concepts. This kind of prototyping is used for observing interaction with external sources, enabling the design team to take a step back and learn from the observations. In the automotive industry, automakers often show off one-of-a-kind concept car projects at large automotive venues to gather external feedback and reactions.

2.4.4. Internal, reflective prototyping

Internal, reflective prototyping is a learning activity, used by the product development team to learn and conceptualize ideas. These prototypes are rough, made for exploring, understanding

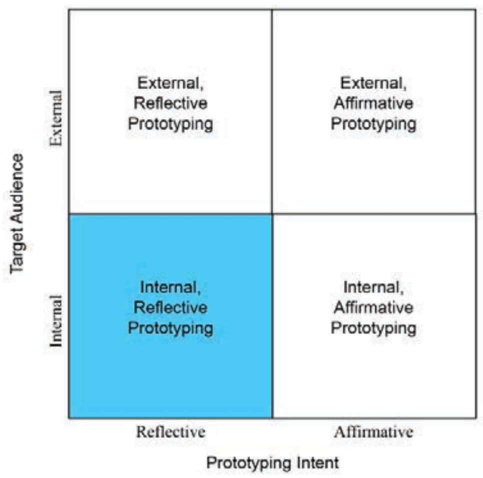

Figure 3 - A proposed model of four prototyping categories.

and experimenting with functionalities that are essential for product success, with the aim of creating new insights within the product development team (21). Typically, internal, reflective prototypes have low fidelity (22), and therefore regarded as waste after a project is finished. These prototypes may prove especially useful when facing high complex problems, like the component layout of an automotive engine bay.

By using terminology from the Tacit Knowledge Framework (23,24), we use the terms ‘knowns’ and ‘unknowns’; Both affirmative prototyping categories are linked to analysis, as they are dealing with known problems and requirements—the ‘known knowns’ (i.e. known articulated problems with known possible solutions). Adversely, reflective prototyping categories aim at exploration, and thus at dealing with unknown problems—the ‘unknown unknowns’ (i.e. non-articulated problems with unknown solutions). Coming from this perspective, we argue that known problems are best solved analytically, while unknown problems are best solved exploratively.

3. Examples: Learning from Prototyping

In the following subsections, the theory presented in the previous section will be accentuated to show the influence of internal, reflective prototyping in product development. The first case considers applying a physical prototype to an analysis for evaluating the numerical method and consequentially learning about the method and saving time in the process. The second case presents a failed crash box, once designed for a new car model that was well analyzed—but still failed due to an overlooked design-manufacturing detail. A discussion of the mistakes is made in light of the theory presented.

3.1. Case I: Applying Physical Computation for a Rotational Spiral Spring

In (25), a case illustrates the effects of combining numerical computations with testing a physical representation of the design. The time required to design a concept by using

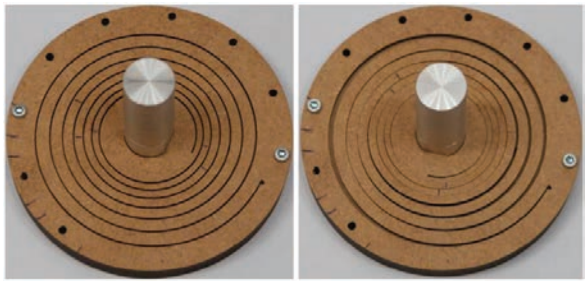

Figure 4 - MDF prototype with markings used to estimate the flex of the rotational spring (25).

analytical tools in complex cases can be greatly reduced by applying a physical prototype for testing and comparison, as proposed in the article.

The case studies a rotational spiral spring that is analyzed by setting up a numerical model (using mechanical spring theory), predicting stiffness and maximum stress of the rotational spiral spring. Meanwhile, a physical model is made with MDF (Medium Density Fibreboard) and tested (Fig. 4). The output data reveals a striking similarity, though the stiffness is somewhat overestimated in the analysis. Although the results are not identical, the combination of the physical and numerical computations shows the numerical analysis to be transferable to the physical dimension and may be scaled further. Combined, these methods yield satisfactory results in a very short time.

This case shows very well how time can be saved by applying internal, reflective prototyping early in the product development process to facilitate faster learning. This approach may prove especially applicable for complex cases, reducing complexity by understanding which analytical tools might be appropriate—and saving time by doing so. As for all internal, reflective prototyping, the prototype used for the physical part of the computation is not applicable in the finished product. However, it facilitates the designers’ learning of how their analytical problem transfers into the physical domain. Internal, reflective prototyping is used to learn from internally, either individually or as a collaborative group, as they typically are low fidelity in nature, but educational and time saving.

3.2. Case II: Crash Box Failure Due to Lack of Variability Testing

In this case, we use an example from a large European automaker, which had designed a crash box for topological optimization, to be fit into a new car model. Crash boxes, separate deformation elements between the front bumper and the front longitudinal rail, are designed to deform on low-speed impact to prevent damage to the rest of the car to reduce the repair cost. The production method of the crash box was extrusion of one open cross-section that was bent, cut, pierced, and welded into a closed box configuration with an integrated foot plate mounted to the rails.

The Danner crash test (26) rates cars at the impact of collision in their ability to minimize costs of repair at 0-15km/h, for the purpose of evaluating the car’s properties to set an insurance premium base. In the Danner test, the crash box

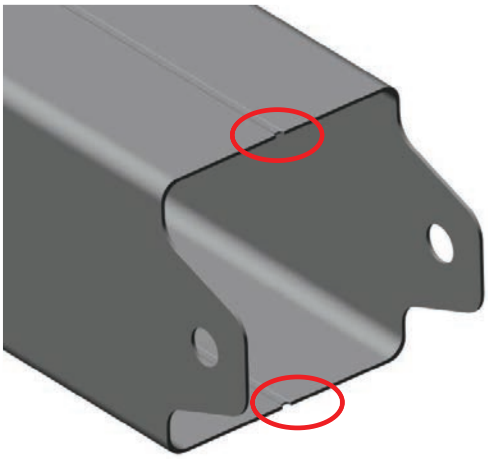

Figure 5 - Exemplification of a crash box, with highlighted area of interest.

of the said model was expected to crush in a controlled manner upon collision test impact without damaging expensive components or activate the air bags, which are the costliest to replace. In the numerous FEA simulations done to optimize the system, the welding configuration was assumed to be geometrically perfect, starting at the very end of the box. However, in production (MIG) welding, start and stop of the weld seam tend to create minor groove of varying magnitude at the very end, depending on dimensional accuracy of the individual part, and other control parameters. Hence, the accuracy of the FEA model was not capable of capturing the local stress state in the vicinity of the grove (as illustrated in Fig. 5). Instead of failing by controlled crushing as predicted in the FEA model, occasionally, the weld seam failed like a zipper starting from the very end of the box once the bumper folded and contacted the very end of the crash box. The fluctuations (in the force deformation curve) triggered the air bag sensors, resulting in the airbags deploying in low speed tests at 15 km/h. This type of failure is considered catastrophic as a consequence of the repair costs associated with replacing the airbags.

The influence of small variations imposed by manufacturing (welding) is a very complex matter. Sensitivity testing of the crash box with the same production-intent premises as the serial produced product would have prevented encountering a failure such a long time after launch. This clearly demonstrates the risk of failing to integrate the product development process and the manufacturing process. The design engineers did not know this would be an issue, and the unspecified 'parameter' related to end configuration (of the weld) remained an unknown until several vehicles were retested after launch.

If the team had engaged in internal reflective prototyping activities, the influence of such critical design features could have been uncovered. The learning outcome in this case could have led the team members to acquire the necessary knowledge to see the disconnection between the manufacturing process and the intended design, possibly identifying a low-cost solution (process or design change) to such a fairly fixable problem.

In this case, properly done internal, affirmative prototyping could have uncovered the problem. However, we would argue that doing internal, reflective prototyping in the early stages of the development process would have facilitated important learning. As a result, the early development process would be less complex, and problems not otherwise perceived as problems would be uncovered. Hence the value of prototyping and testing to learn—not only to verify—could have significantly saved time, money and averted the ultimate failure of the design.

4. Research Potential of Using Explorative and Analytical Methods for Learning in Product Development

Furthermore, the insights, experience and learnings present a unique research opportunity, since improved understanding of the creation and transfer of tacit knowledge will alter how we facilitate the product development process. Hence, there is a call for more research concerning how tacit knowledge influences the development of products with high levels of complexity, especially when dealing with many unknown unknowns.

As identified in (27), there is a gap between professional knowledge and real-world practice. In his works, Simon applies methods of optimization from statistical decision theory, thus laying a foundation for a scientific approach to treating knowledge. Adversely, Schön (28) argues that the real challenge lies not within the treatment of well-formed requirements, but rather the extraction of such requirements—practically unknown unknowns—from real world situations. In (29), Schön presents reflective iteration rounds as a learning tool of great potential. Taking this perspective, we argue that reflective prototyping may be used as a learning tool in handling unknown unknowns in product development.

Ultimately, we argue that, in reality, product development requires balancing of the tacit and the explicit, the explorative and the analytical. We have seen that disconnection between product development and manufacturing processes cause major implications for entire value chains. In hindsight, exploration and experience of manufacturing techniques and challenges could have led to the discovery of potential risks and problems in the product development process (unknown unknowns), and—if so—how to best balance analysis and exploration for uncovering these unknowns in a cost and resource efficient manner?

5. Conclusion

The purpose of this paper has been to accentuate the possibilities of using prototyping in product development for manufacturing settings. An attempt has been made to map future opportunities, both for industry and academia, and a call for the recognition of prototyping as a time saving learning tool. The potential of applying exploration by interaction with prototypes related to knowledge capture, transfer and learning is demonstrated in the context of the automotive industry. Thus, a call for increased focus on mixing analytical (e.g. simulations) and explorative (e.g. prototyping) approaches is presented as a viable direction for further efforts in both industry and academic communities.

Altogether, the importance of understanding the interplay between (tacit) knowledge, explorative and analytical approaches to problems in product development and manufacturing, and the role of prototyping for learning are topics that require further pursuit.

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